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Assessing edge cracking resistance in AHSS automotive parts by the Essential Work of Fracture methodology

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Abstract. Lightweight designs and demanding safety requirements in automotive industry are increasingly promoting the use of Advanced High Strength Steel (AHSS) sheets. Such steels present higher strength (above 800 MPa) but lower ductility than conventional steels. Their great properties allow the reduction of the thickness of automobile structural components without compromising the safety, but also introduce new challenges to parts manufacturers. The fabrication of most cold formed components starts from shear cut blanks and, due to the lower ductility of AHSS, edge cracking problems can appear during forming operations, forcing the stop of the production and slowing down the industrial process.

Forming Limit Diagrams (FLD) and FEM simulations are very useful tools to predict fracture problems in zones with high localized strain, but they are not able to predict edge cracking. It has been observed that the fracture toughness, measured through the Essential Work of Fracture (EWF) methodology, is a good indicator of the stretch flangeability in AHSS and can help to foresee this type of fractures.

In this work, a serial production automotive component has been studied. The component showed cracks in some flanged edges when using a dual phase steel. It is shown that the conventional approach to explain formability, based on tensile tests and FLD, fails in the prediction of edge cracking. A new approach, based on fracture mechanics, help to solve the problem by selecting steel grades with higher fracture toughness, measured by means of EWF. Results confirmed that fracture toughness, in terms of EWF, can be readily used as a material parameter to rationalize cracking related problems and select AHSS with improved edge cracking resistance.

1. Introduction

AHSS present excellent mechanical properties that poses them as a great option for safety components, structural parts of the car body and chassis, reducing the total vehicle mass and enhancing crashworthiness. Their use in the automotive industry has been strongly extended in the last two decades in order to fulfill the more and more demanding safety and fuel consumption legislations [1]. The use of this kind of steels has introduced new issues that are not completely solved. One of them is the edge cracking in cold formed sheet components. AHSS present high strength (600-1200 MPa) but limited ductility, compared to conventional mild steels, which makes them more sensitive to premature cracking during cold forming operations, especially in trimmed, sheared or punched areas, where the material is damaged and defects, such as micro cracks can be present [2-4]. These defects can trigger the crack propagation through the sheet thickness during the subsequent cold forming processes and lead to the fracture of the component [4]. Figure 1 shows some examples of cracks in cold formed components.

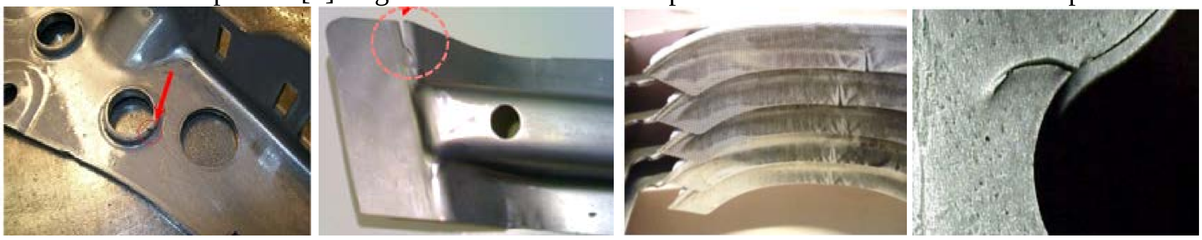

Figure 1. Examples of edge cracking in cold formed components

Intensive research has been made on this issue and great efforts have been put on the development of failure criteria to predict this type of fractures. It has been shown that conventional approaches, such as FLD or tensile tests are not valid to predict them [5-6]. Hence, additional tests are required to quantify the edge cracking sensitivity of AHSS. In this regard, stretch flangeability, measured by the Hole Expansion Test (HET), has shown to be suitable to foresee edge cracking related problems and has become an important parameter to consider in AHSS sheets formability [7].

Previous works showed that stretch flangeability of AHSS is governed by the crack propagation resistance of the material [8-11]. Casellas et al. analysed the correlation between stretch flangeability and fracture toughness (in terms of *Essential Work of Fracture*, *EWF*) on several AHSS grades with different microstructure and a quite good correlation between the two parameters was found [10]. AHSS showing higher EWF values presented higher Hole Expansion Ratio (HER), i.e. the tougher the material the greater the stretch flangeability. Other authors found the same trend between HER and J_c values [11]. Thus, fracture toughness, could be used to rationalize edge cracking and rank the stretch flangeability of AHSS.

Nevertheless, within the frame of Elastic Plastic Fracture Mechanics (EPFM), no standard methods are available to readily measure the fracture toughness of thin steel sheets presenting plane stress conditions. Conventional EPFM methodologies (J-Integral, CTOD, J-R curves, etc.) are standardized for plane strain conditions and their implementation requires exhaustive sample preparation, time consuming tests with constant monitoring and rigorous data treatment [12].

The EWF methodology was developed by Cotterell and Reddel [13] in the 80s as an alternative to measure the fracture toughness of thin plates under plane stress and was applied successfully to polymers [14-16] and ductile metals [17-20]. More recently, the methodology has been applied to AHSS sheets and has shown to be appropriate to evaluate the fracture toughness [10, 21-23]. The main advantage of this methodology is the relative easiness of the procedure compared to the other methods.

This work aims to provide a reliable tool, based on fracture mechanics, able to discern the edge cracking sensitivity of AHSS sheets and avoid unexpected fractures in industrial cold formed components. For this purpose, a serial production automotive part has been studied. The component presented multiple cracks in stretched flanges when manufactured with a dual phase (DP) steel (figure 2). The problem was solved replacing the DP steel grade by a complex phase (CP) steel with the same maximum strength and thickness. Different mechanical tests, including an EPFM-based one, were used to assess the edge cracking resistance of AHSS.

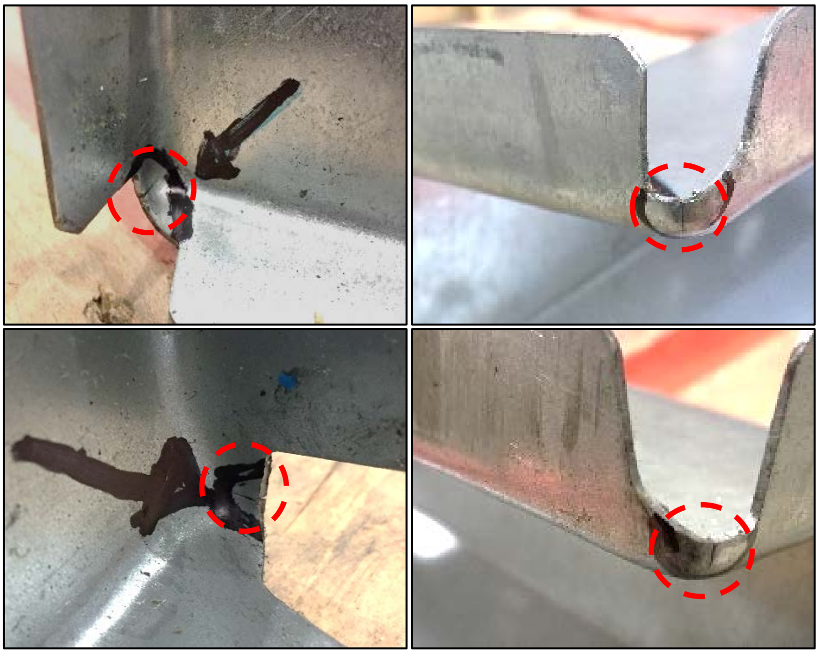

Figure 2. Edge cracks observed in the component manufactured with DP steel grade.

2. Materials

The materials investigated were two 1st generation AHSS grades of 1000 MPa UTS, commonly used for lightweight automotive components: a DP steel and a CP steel. Both steel grades are presented in form of sheets of 1.2 mm thickness. The chemical composition of the steels is shown in table 1. A basic microstructural characterization was performed by means of Scanning Electron Microscopy (SEM). The results are shown in figure 3. DP1000 presents a matrix consisting on a mixture of ferrite and martensite whereas CP1000 exhibits a more homogeneous microstructure, consisting on a bainite/tempered martensite matrix.

Table 1. Chemical composition of the studied steels (in wt%)

Steel grade	C	*Si*	Mn	*Cr*	B	*Al*
CP1000	~0.1	<0.5	1.8-2.2	<0.7	<0.003	-
DP1000	~0.15					

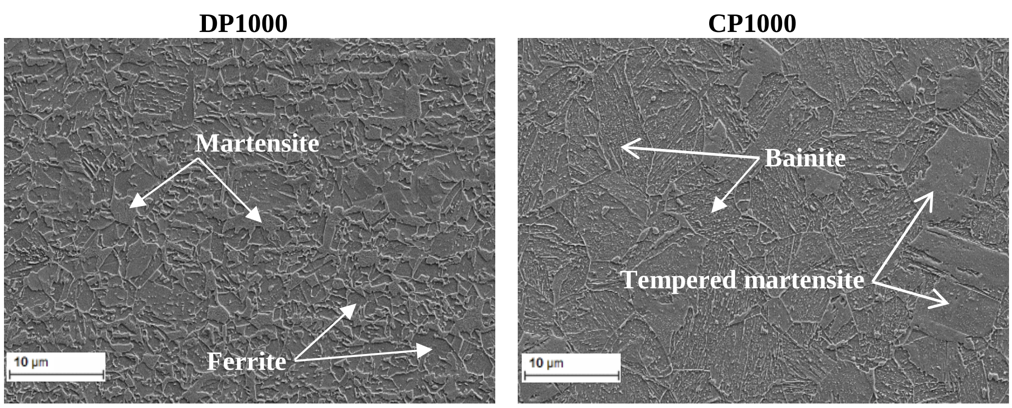

Figure 3. Microstructures of DP1000 (left) and CP1000 (right).

3. Experimental results

In order to characterize the fracture resistance of the studied steel sheets and rationalize the cold forming behaviour, different mechanical tests were performed.

3.1. Tensile tests

Conventional uniaxial tensile tests according EN-ISO 6892 were performed at transverse orientation respect to the rolling direction with an initial gauge length of 80 mm. 3 specimens per material were tested. Engineering stress-strain curves obtained from tensile tests are shown in figure 4a and tensile parameters are summarized in table 2.

Both steel grades present identical maximum strength. DP1000 shows low yield strength, a great strain hardening and large elongation. On the other hand, CP1000 exhibits higher yield strength, but lower work hardening rate and elongation. Such mechanical properties are controlled by their complex microstructures. In DP steels, the combination of a soft ferritic matrix and hard martensitic phases provides good ductility and attain high tensile strength. The great work hardening rate is caused by the limited deformation of ferrite due to the presence of hard martensite islands, which means higher rate of dislocations accumulation. The homogeneous multiphase microstructure of CP steels leads to attain higher yield strength, but the elongation obtained in this kind of steels is smaller than in DP.

Table 2. Tensile parameters at transverse direction: yield strength (σ_{ys}), Ultimate Tensile Strength (σ_{UTS}), elongation at fracture and work hardening coefficient (n).

	t [mm]	σ_{ys} [MPa]	σ_{UTS} [MPa]	Elongation at fracture [%]	$n_{2\text{-}4\%}$	Area under tensile curve [MPa*%]
DP1000	1.2	697	1018	11.99	0.18	11286
CP1000	1.2	904	1022	7.97	0.07	7677

3.2. Formability tests

Formability of the two steel grades has been assessed through Nakajima stretching tests. They were performed according to ISO 12004 to obtain the Forming Limit Curves (FLC). Grease, Teflon and polyurethane disks were inserted between the punch and the sample to minimize the friction between the parts. Six different geometries were used to obtain the different strain paths and determine the FLCs (figure 4b). 3 specimens for each geometry were evaluated. A blank holder force of 600 kN was applied and the punch speed was set to 90 mm/min.

DP1000 shows higher FLC_0 (plain strain) value and greater formability on the right side of the FLD, corresponding to biaxial strain modes. In the left side of FLD (uniaxial strain paths) CP1000 shows slightly better behaviour. However, the information corresponding to negative minor strains is limited, since the level of minor strain reached with the tested geometries is low, especially for CP1000 (minimum minor strain: 0.03).

3.3. Stretch flangeability tests

HET were performed according to ISO 16630 [7] to evaluate the stretch flangeability of the investigated AHSS. 6 specimens per each material were evaluated. The tests were conducted with a punch speed of 1 mm/s and a clamping force of 600 kN was applied to avoid any material draw-in from the clamping area during the test. The initial hole diameter was 10 mm and the cutting tolerance was set to 12 %.

The value obtained from HET is the HER, which represents the maximum diametric expansion that a circular punched hole can reach when a conical tool is forced into it until a crack in the hole edge extends through the full sheet thickness.

HER values are plotted in figure 4c. DP1000 shows HER values from 12 % to 22 % and CP1000 from 47 % to 84 %. Such high variability has been previously reported by other authors [24, 25].

CP1000 shows much larger hole expandability than DP1000. The lower stretch flangeability of DP steels is explained by the hardness difference between the ferrite and martensite phases. On the other hand, the smaller difference in properties between phases and lower internal stresses in CP grades lead to improved hole expansion behaviour [2, 9].

3.4. Essential Work of Fracture tests

The fracture toughness of the studied AHSS grades was evaluated by means of the EWF tests. EWF tests are performed following the procedure stablished in the European Structural Integrity Society (ESIS) protocol [26]. Rectangular Double Edge Notched Tensile (DENT) specimens of 90 x 40 mm were extracted from the cold formed components at 0º respect to the rolling direction. A total of 10 specimens per material were tested with 4 different ligament lengths ranging from 7 to 14 mm. 2 specimens were evaluated for each intermediate ligament (9 and 11 mm), whereas for the extreme ligament lengths (7 and 14 mm) 3 specimens per ligament were tested.

The tests were performed at a constant cross-head speed of 1 mm/min and a gauge length of 25 mm was used. To avoid the effect of notch root radius in the fracture toughness evaluation, fatigue pre-cracks were introduced on the notch root. It must be noted that w_e is not fully a material intrinsic property but it is influenced by the sheet thickness, since plane stress fracture toughness depends on the volume available to deform plastically at the front of crack tip. Hence, w_e is a fracture toughness value for the evaluated sheet thickness.

Figure 4d shows the EWF results obtained for DP1000 and CP1000 steel grades. It is observed that CP grade exhibits much greater fracture toughness than DP. Remarkable differences in toughness between CP and DP steel grades were reported previously by other authors [3, 10].

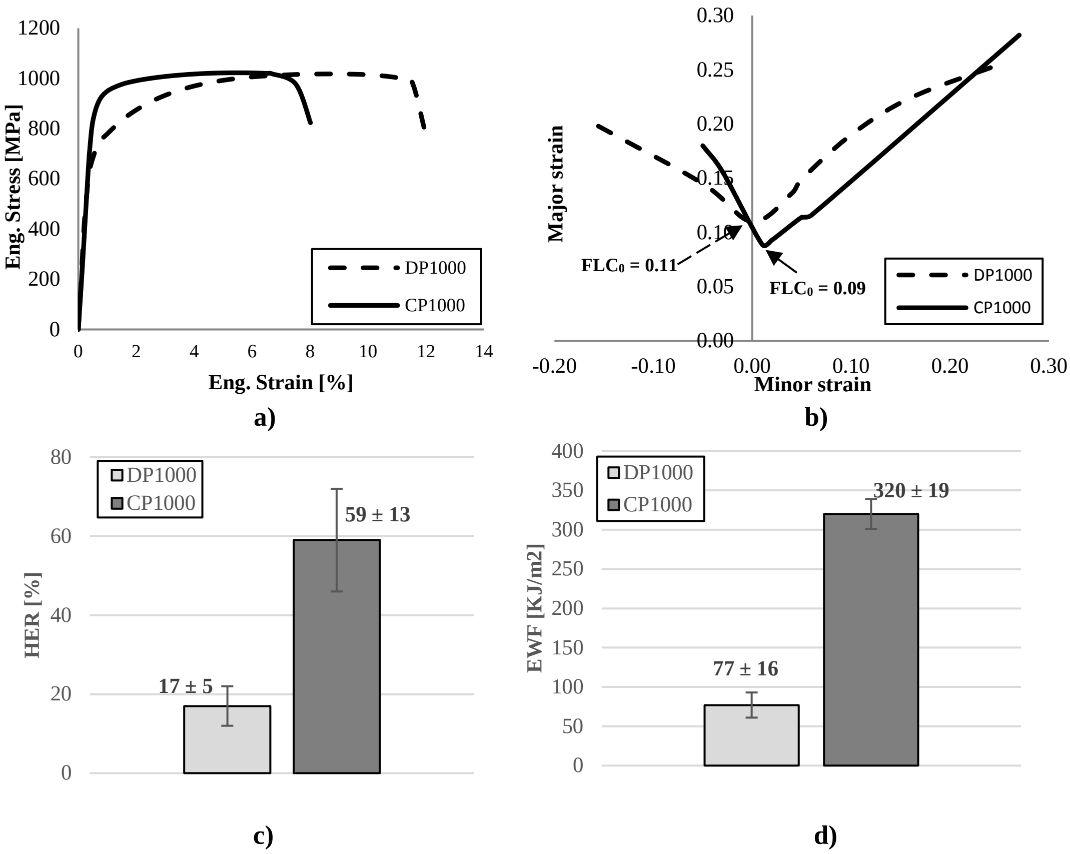

Figure 4. Experimental results obtained with the investigated CP and DP grades. a) Tensile curves, b) FLCs, c) HER values and d) EWF values.

4. Discussion

DP1000 shows much greater elongation than CP1000 in tensile tests, what would indicate higher ductility of the DP grade, and much higher n-value, generally associated to greater formability. However, DP1000 showed extensive edge cracking compared to CP1000. It must be noted that tensile tests evaluate only global damage. The fracture elongation obtained is an average strain along a gauge length and such strain value totally underestimates the local ductility potential of the material. Hisker et al. found that the microstructure of DP-steels is more sensitive to localized damage but it is compensated by the great work-hardening [28]. Thus, DP steels present great tensile properties but poor stretch-flangeability. However, the homogeneous microstructure of CP-steels is less sensitive to localized damage but has limited capacity for work-hardening, which leads to lower elongation in tensile tests but higher edge stretchability [28].

Fracture energy extracted from tensile test is also not suitable to describe edge cracking. Classical toughness definitions are based on the energy obtained from the area under the engineering curves and, usually, higher energy is associated with higher toughness (figure 4a, table 2). DP1000 shows higher fracture energy than CP1000. Hence, such energy values do not describe edge cracking.

DP1000 also shows higher FLC_0 than CP1000 (figure 4b), but again, this value cannot be used to understand edge cracking. FLD is suitable to evaluate the formability of AHSS when general deformation modes are present, but for shearing or edge stretching a poor correlation is obtained and FLC fails to predict the fracture [6]. The deformation mode for edge stretching is uniaxial tension. The fracture of the specimens in FLD tests at uniaxial tension is preceded by localized necking in the bulk material. Thus, the fracture strain determined overestimates edge cracking, which occurs before considerable necking at a much lower strain level [5, 24].The different edge crack behavior showed by DP1000 and CP1000 cannot be explained by means of conventional approaches, i.e. fracture elongation from tensile tests or FLC.

HET has shown to be suitable to estimate the stretch flangeability of AHSS [5, 24 and 27]. HER values obtained from the investigated steels (figure 4c) highlight the greater edge cracking resistance of CP steel grade against DP steel. The poor stretch flangeability showed by the DP justify the appearance of multiple edge cracks, observed in the cold formed component. However, the big scattering observed in the measurements can lead to question the objectivity of the method to characterize edge cracking sensitivity. Such scatter is attributed to the high number of variables during the test: amount of damage introduced during punching, method of crack detection, etc.

Fracture toughness measured in the frame of EPFM, through the EWF tests, can also be used as a material property to understand edge cracking. The EWF measurements carried out show that the fracture toughness of the CP1000 steel grade is much greater than the DP1000 steel ones (figure 4d) and it is found that higher EWF is related to greater HER values (figure 4c). Hence, the EWF is able to rationalize the poor edge cracking resistance of DP1000 and justify the appearance of multiple cracks at the edges of the cold formed component. This is in agreement with previous works that showed a very good correlation between HER and EWF [3, 10]. Such authors proposed EWF as an alternative method to evaluate the stretch-flangeability of AHSS. The results obtained in the present work are in good agreement with these investigations and support such proposal.

As a matter of comparison, the values of EWF and HET obtained here are plotted together with results from reference [10], in figure 5. It can be observed that results fit quite well in the almost linear correlation, and allows pointing out EWF as a material property and a reliable experimental parameter to evaluate stretch-flangeability of CP and DP steels and predict edge crack sensitivity.

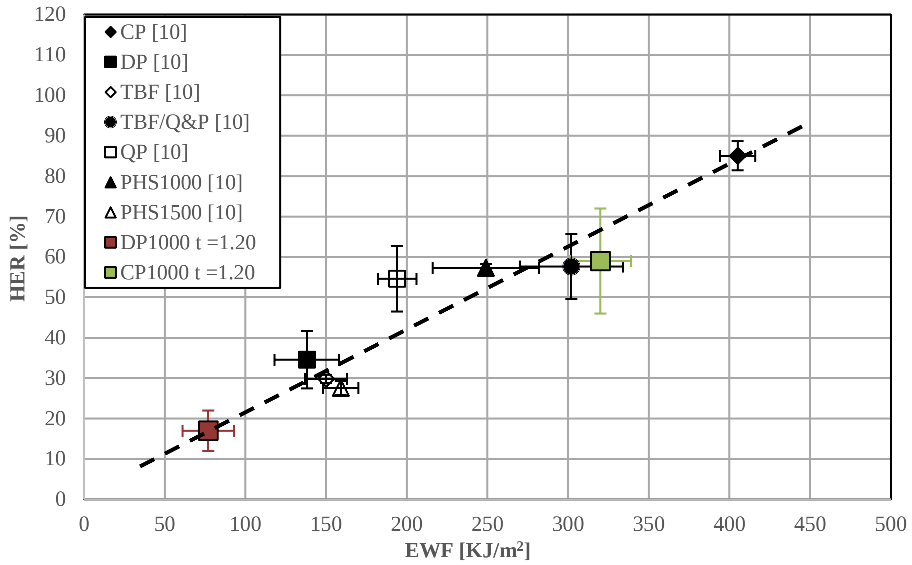

Figure 5. EWF against HER. CP and DP steel grades investigated in this work together with other AHSS grades reported in reference 10.

5. Conclusions

From the investigations carried out in this work with a serial produced AHSS automotive component and with the results of different mechanical tests, the following conclusions can be drawn:

- Conventional approaches, such as FLD or tensile tests are not capable to predict edge cracking sensitivity of DP and CP steels.
- It is shown that EWF methodology is a reliable tool to evaluate the fracture toughness of CP and DP steel grades and can properly rationalize edge cracking related problems.
- EWF is proposed as a parameter to select AHSS grades with improved stretch flangeability and avoid unexpected edge fractures during cold forming processes.

Acknowledgments

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